Australian Government

Great Barrier Reef
Marine Park Authority

Impacts of tropical cyclone Yasi on the Great Barrier Reef

A REPORT ON THE FINDINGS OF A RAPID ECOLOGICAL IMPACT ASSESSMENT

JULY 2011

Australian Government

Great Barrier Reef
Marine Park Authority

Impacts of tropical cyclone Yasi on the Great Barrier Reef

A report on the findings of a rapid ecological impact assessment

July 2011

Published by the Great Barrier Reef Marine Park Authority

ISBN 978 1 876945 66 4 (pdf)

National Library of Australia Cataloguing-in-Publication entry

Impacts of tropical cyclone Yasi on the Great Barrier Reef [electronic resource] : a report on the findings of a rapid ecological impact assessment, July 2011 / Great Barrier Reef Marine Park Authority.

ISBN 978 1 921682 45 2 (pdf)

Includes bibliographical references.

Cyclones--Queensland--Great Barrier Reef Region.
Cyclones--Environmental aspects--Queensland--Great Barrier Reef.
Coral declines--Queensland--Great Barrier Reef.
Cyclone Yasi, 2011.
Great Barrier Reef Marine Park (Qld.)

Great Barrier Reef Marine Park Authority.

551.551309943

Acknowledgements
This report was compiled and edited by Dr Paul Marshall, Roger Beeden, Jen Dryden and Jeremy Goldberg of the Great Barrier Reef Marine Park Authority.

This publication should be cited as:
Great Barrier Reef Marine Park Authority 2011, *Impacts of tropical cyclone Yasi on the Great Barrier Reef: a report on the findings of a rapid ecological impact assessment, July 2011*, GBRMPA, Townsville.

Requests and inquiries concerning reproduction and rights should be addressed to:

Australian Government
Great Barrier Reef
Marine Park Authority
Director, Communication and Education Group
2-68 Flinders Street
PO Box 1379
TOWNSVILLE QLD 4810
Australia
Phone: (07) 4750 0700
Fax: (07) 4772 6093
info@gbrmpa.gov.au

Comments and inquiries on this document are welcome and should be addressed to:

Director, Climate Change Group
climate.change@gbrmpa.gov.au

www.gbrmpa.gov.au

CONTENTS

EXECUTIVE SUMMARY

Tropical cyclones can be very destructive, often causing severe and widespread damage to coastal communities, infrastructure and ecosystems. In many coral reef regions, cyclones and other storms are among the most important structuring forces, influencing coral cover, species diversity, productivity and reef morphology. In the Great Barrier Reef, storms have been attributed with causing 34 per cent of the coral mortality recorded between 1995 and 2009[1]. Extreme intensity cyclones (category 4-5) are especially important in shaping coral reef communities, having the potential to cause severe damage to benthic reef communities and the underlying reef structure over hundreds of square kilometres[2]. While storms of this magnitude are generally considered rare, the Reef has already experienced four extreme intensity cyclones this century. The most recent of these, tropical cyclone Yasi, was considered to be one of the largest and most powerful cyclones to affect Australia since records began.

Tropical cyclone (TC) Yasi passed over the Great Barrier Reef on 2-3 February 2011 (Figure 1). It originated in the South Pacific Ocean north of Vanuatu and quickly developed to a category 5 storm as it travelled southwest towards the Reef. The cyclone attained a minimum central pressure of 929 hPA, maintaining intensity to become the first category 5 system to cross the Queensland coast since 1918[3,4]. At its peak, TC Yasi created wind gusts of 285 km/h and its immense size meant that gale force winds were experienced along nearly 760 km of coastline between Mackay and Cooktown.

In February and March 2011, the Great Barrier Reef Marine Park Authority (GBRMPA), in partnership with the Queensland Parks and Wildlife Service (QPWS) and Australian Institute of Marine Science (AIMS) and supported by other partners including the tourism and commercial fishing industries, surveyed coral reefs exposed to the destructive force of TC Yasi. These surveys provided a rapid assessment of the nature and spatial extent of damage to benthic communities of the Great Barrier Reef. The joint teams completed 882 rapid reef health surveys at 76 reefs spanning 500 km of the Great Barrier Reef Marine Park between Port Douglas and Airlie Beach. The results of the surveys will help managers and reef users understand the implications of extreme intensity cyclones, which are predicted to occur more frequently under a changing climate[5,6,7].

The damage from TC Yasi was extensive. Overall, coral damage was reported across an area of approximately 89,090 km^2 of the Great Barrier Reef Marine Park. In total, approximately 15 per cent of the total reef area in the Marine Park sustained some coral damage and six per cent was severely damaged. Most of the damage occurred between Cairns and Townsville. Reefs beyond the northern limit of the destructive wind band (around Port Douglas) appear to have escaped severe damage, although tourism operators reported minor damage at some sites, especially those characterised by high cover of fragile branching and plate corals. Surveys of inner shelf reefs between Townsville and the Whitsundays recorded low levels of recent reef damage. However, reports by commercial fishers of the emergence of new cays and large rubble banks offshore from Bowen are indicative of the substantial wave energy generated by TC Yasi in areas south of the edge of the destructive wind boundary.

Although spanning a wide area, the damage caused by TC Yasi was patchy, ranging from extremely severe to very minor. At the worst affected sites the impact of waves and wave-borne debris removed almost all traces of sessile (attached) marine life down to at least 15 m depth. At these sites fine filamentous algae blanketed large sections of recently exposed substrate at the time of the surveys, especially on shallower (<5 m) reef areas. Reefs closer to the eye of the storm suffered the most damage and with reefs to the south of the eye were more severely damaged than reefs to the north. Damaged corals were recorded on most of the reefs surveyed, however some reefs were also observed to have areas that suffered relatively minor damage, where the majority of corals were still attached and the underlying substrate mostly unaffected. Often, relatively undamaged patches of reef could be found within 50-100 m of severely damaged patches. Areas of healthy reef were observed even within the region exposed to very destructive winds, although undamaged reef areas were increasingly rare with proximity to the centre of the cyclone's path. Within the very destructive wind boundary, sites with only minor damage were more likely to be situated on leeward sides of reefs that were part of a cluster of reefs and therefore somewhat sheltered from the cyclone-generated waves and currents. The patchiness of damage observed following TC Yasi is consistent with observations of damage from other intense cyclones[8,9].

Coral reefs have a natural resilience to physical disturbances such as cyclones. As a result, damaged reefs can often recover relatively quickly if they are free from other stresses[8,10,11,12]. Long-term monitoring of reefs following previous cyclones indicates that a severely damaged reef can show strong signs of recovery within about five to 15 years, if there is rapid recruitment and good survivorship of fast-growing corals (such as *Acropora* and *Pocillopora* species)[9,13,14]. However, more substantial recovery, represented by moderate coral cover comprising a diversity of species (including slow-growing types such as *Porites sp*. or *Favites sp*.) and larger colonies, can take several decades[8,14]. The patchiness of the damage following TC Yasi suggests that recovery of reefs in the affected area will be similarly variable. Given the current outlook, and assuming the region is not affected by future impacts such as other cyclones, crown-of-thorns starfish or coral bleaching, most reefs with low to moderate level damage can be expected to show signs of recovery within five years. However, the ecological legacy of the impacts from this extreme intensity cyclone is likely to be evident for several decades on reefs most affected by TC Yasi.

Effective management is critical to the optimal recovery of damaged reefs, so current efforts to build reef resilience will be particularly important for areas affected by major disturbances such as TC Yasi. Progress in halting and reversing the decline in water quality affecting damaged reefs will be especially important, as processes of reef recovery are highly vulnerable to elevated levels of nutrients, sediments and pollutants. In addition, coral reefs are expected to experience major disturbances more frequently due to climate change. The Reef has already experienced an increase in the frequency of severe cyclones and coral bleaching events[15]. These portents of climate change provide an important opportunity to better understand the outlook for the Reef, and to improve our ability to manage the Great Barrier Reef Marine Park in a changing climate.

INTRODUCTION

Tropical cyclones can cause severe and widespread damage to coral reefs. Heavy rainfall associated with cyclones can lead to extensive flood plumes and lowered salinities that stress or kill sensitive organisms such as corals and seagrasses, while the waves and currents generated by extreme-velocity winds can cause severe and widespread physical damage[1,2,6,8]. In addition to the direct effects of wave and currents, coral rubble and boulders mobilized by the storm's energy cause impacts to reef organisms and the underlying reef substrate[8,16,178,15,17,18].

The combination of impacts from a cyclone can result in severe damage, including complete destruction of reef communities and severe scouring of substrate over large areas of reef. However, differences in levels of exposure to cyclone-related forces, and differences in the sensitivity of different species and reef habitats, means that damage is variable; there are often reef areas that suffer only minor damage, even in areas exposed to extreme winds[16]. The destructive potential of cyclones makes them a major influence on the structure and development of coral reefs[2,16].

The Great Barrier Reef spans an area that is regularly exposed to cyclones and their damaging forces. Between 1970 and 2006 the region experienced 116 cyclones. The ecological importance of storms is captured in a recent analysis of the long term monitoring data collected by AIMS, which showed that approximately 34 per cent of the coral mortality recorded between 1995 and 2009 in the Great Barrier Reef was attributable to storms[1.] The more intense storms are thought to be particularly important in the dynamics and evolution of reef ecosystems, and these appear to be increasing in frequency. For example, the last three decades have seen the frequency of severe cyclones (category 3-5) almost double[6,19]. An increase in the frequency of severe cyclones by half a category has been predicted to increase coral mortality by 60 per cent[9], with resultant impacts for reef-dependent communities and industries.

The significance of cyclones to the Great Barrier Reef has recently been demonstrated by the dramatic impacts caused by two large category 5 cyclones that have affected the Reef in the last few years. TC Hamish caused extensive reef damage when it traversed along the outer edge of the southern Great Barrier Reef for around 500 km in 2009. Many reefs suffered severe damage, with flow-on affects to associated species and habitats, as well as to Reef-dependent industries such as the commercial line fishery [20]. While TC Hamish did not cross the coast (and therefore did not cause major damage to coastal towns and infrastructure), it was quickly recognized as the most destructive cyclone to have affected the Reef since the early 1900s.

Two years after TC Hamish hit the Great Barrier Reef, TC Yasi entered the region and crossed the Queensland coast near Mission Beach (Figure 1). Making landfall on February 3, 2011, TC Yasi was considered to be one of the largest and most powerful cyclones to affect Australia since records began[3]. The Bureau of Meteorology rated TC Yasi a category 5 with estimated maximum wind gusts of 285 km/h close to the eye. Large areas of the Reef were exposed to the damaging effects of TC Yasi. The wind boundaries of the cyclone were very large: nearly 26 per cent (89,090 km^2) of the 344,800 km^2 Marine Park was exposed to at least gale force winds, and just over 13 per cent (45,768 km^2) was exposed to destructive or very destructive winds. In total, 775 of the 2900 reefs within the Marine Park boundary were within areas exposed to gale force, destructive or very destructive winds[4.]

Even in the context of a long history of cyclone exposure, the size and intensity of TC Yasi indicated that this storm had the potential to have caused an unprecedented amount of damage to the Great Barrier Reef ecosystem.

This report presents the results of surveys conducted to assess the spatial extent and severity of physical damage caused by TC Yasi to the coral reefs of the Great Barrier Reef Marine Park. An understanding of the impacts of extreme intensity storms is important for effective management of coral reefs, which are under increasing pressures from human use and climate change[15]. While the Reef is likely to fare better than most reef regions around the world, impacts from extreme weather events can have lasting impacts on affected reefs and significant implications for Reef-based industries. Understanding the impacts and implications of these events is essential to the refinement and further development of management strategies and policies that support the resilience of the Great Barrier Reef ecosystem and Reef-based industries in the face of climate change[15].

This study is part of the Extreme Weather Response Program, implemented by GBRMPA in response to the extreme weather events of 2010-2011 Australian summer, with additional funding through the federal government's Caring for our Country Program.

IMPACT ASSESSMENT METHODS

The surveys of reef damage utilised a rapid assessment approach to: (1) survey the severity, extent and spatial pattern of recent damage to reefs exposed to potentially damaging winds of TC Yasi and (2) collect photos and video to illustrate the nature of damage to coral communities from extreme intensity cyclones. Where feasible, the surveys targeted reef sites for which there was data on pre-cyclone reef condition and/or that were part of ongoing monitoring programs. This was done to maximise their value to longer-term studies of reef health and resilience in the face of climate-related disturbances.

Between 10 February and 17 March 2011, tGBRMPA and QPWS, in partnership with the tourism and commercial fishing industries and AIMS, surveyed 76 reefs to assess the impact of TC Yasi on the Reef (Figure 2). In total, the surveys covered nearly 10 per cent (73 / 775) of the reefs within TC Yasi's gale force, destructive and very destructive wind boundary (Figure 1)[21] and three additional reefs just

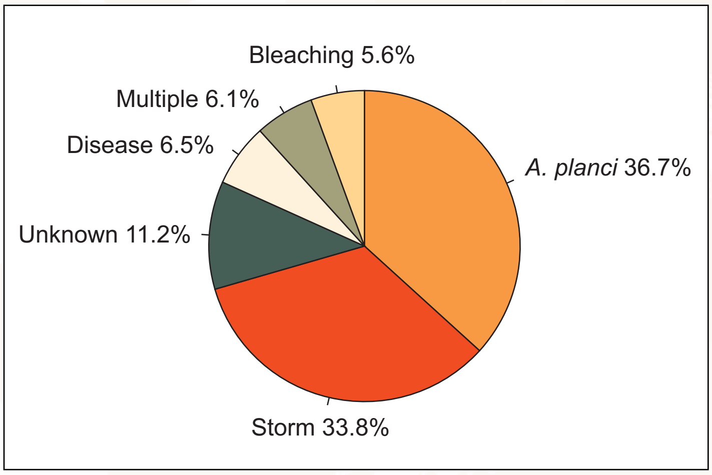


Figure 1: The leading causes of coral mortality on the Great Barrier Reef during the past 16 years. Crown-of-thorns starfish (*a.planci*) and storms were associated with the greatest coral decline over this period. Although coral bleaching was widespread in 1998 and 2002, coral mortality was relatively low[1]. This figure does not include mortality caused by TC Hamish or TC Yasi.

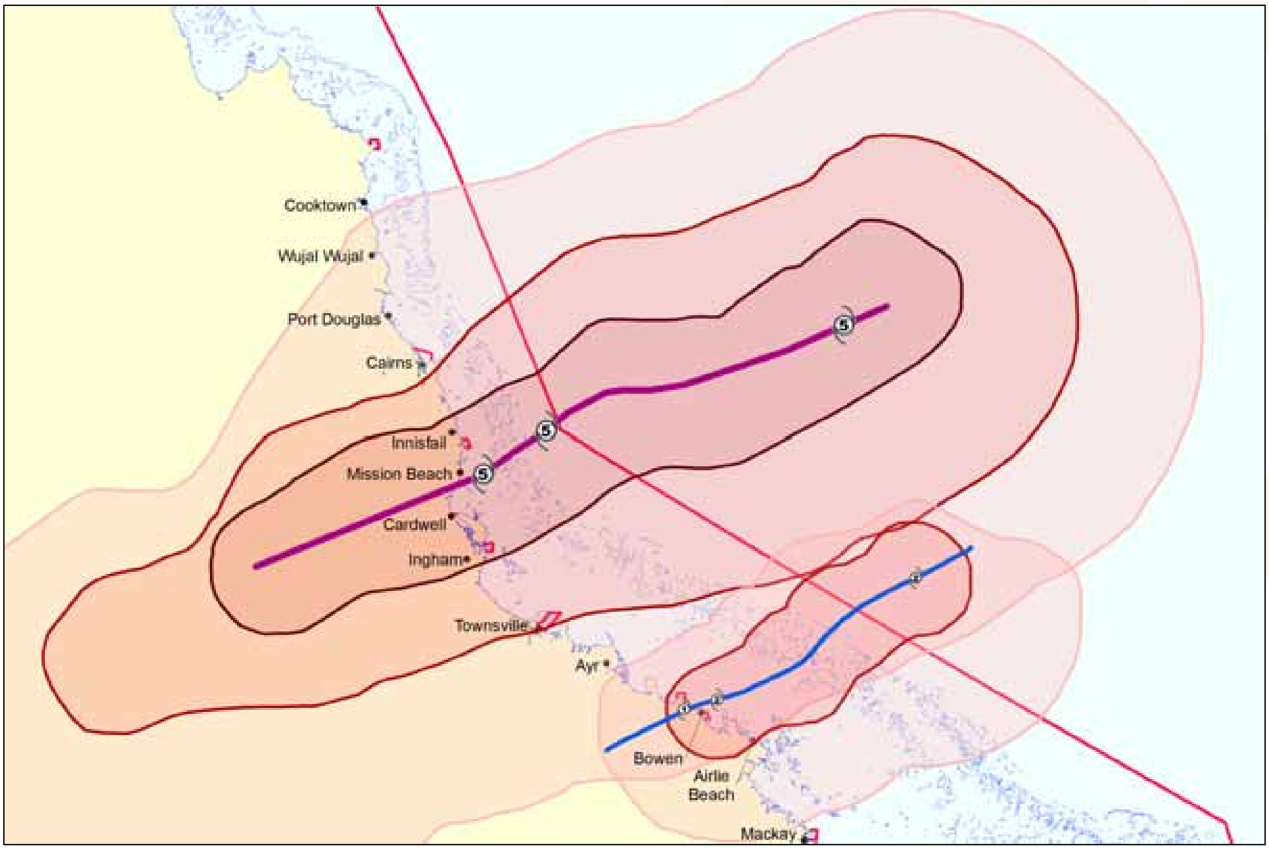


Figure 2: Overlapping TC Yasi and TC Anthony track maps. Light pink outer rings (TC Yasi and TC Anthony) are the gale force wind boundaries (90 - 124 km/h winds), dark pink rings (TC Yasi and TC Anthony) are the destructive wind boundaries (125 - 164 km/h winds) and the innermost maroon ring (TC Yasi only) represents the very destructive wind boundary (165 - >280 km/h winds). The illustrated rings represent 'snapshots' of the TC Yasi and TC Anthony wind boundaries. The impact of each cyclone on the reef and coastal communities is a function of the exposure to extreme winds speeds and the length of time of that exposure; the larger the cyclone, the longer affected areas are exposed to damaging winds[5,6].

outside the gale force boundary (Figure 2). Reefs were selected to represent the range of wind exposure levels, shelf positions (inshore to offshore), distances from the track of the eye of the cyclone (north and south), zoning arrangements and levels of use. In total 15 inshore, 35 mid shelf and 26 offshore reefs spanning four sectors (Cairns to Hinchinbrook Island, Hinchinbrook Island to Townsville, Townsville to Bowen and Bowen to the Whitsundays) were assessed using the Reef Health and Impact Survey (RHIS) protocol developed under the joint GBRMPA-QPWS RHIS program.

The RHIS program has been developed to enable the collection of standardised, quantifiable reef health data suitable for rapid assessment of the impact of events such as flooding, coral bleaching, disease, predation and tropical cyclones (e.g. event severity and extent) as well as human impacts such as anchor damage.

Where conditions permitted, the windward and leeward aspects of each reef were surveyed to assess the extent, severity and patchiness of cyclone damage. Most assessments were done on snorkel and focused on the upper reef slope. Surveys of sites that are part of the AIMS Long Term Monitoring Program[18]. were done on SCUBA to enable damage to be assessed for both the upper and lower slope, and thus enable comparison with long-term data from these sites. Teams completed a minimum of three surveys for at least three sites around each reef (Appendix 1). RHIS impact assessment teams recorded cyclone damage over a series of randomly selected five metre radius circle plots (78.5 m^2) at each site. Surveyors categorised both the extent and severity of the coral damage within each RHIS area. The extent of the damage was recorded as the proportion of coral cover affected within the survey area, whilst severity was evaluated using categories. The damage severity categories describe the most common characteristic of the hard coral colony damage in the RHIS area: Category 1 = colony tips / edges; Category 2 = colony parts / branches; Category 3 = whole colonies (Appendix 1).

Whilst reef framework or structural damage was not a specific category on the survey form, coral colony damage above level three was typically accompanied by increasingly severe impacts to the underlying substrate (Figure 3). Sites suffering structural / reef framework damage were characterised by extensive rubble fields of live and dead coral fragments, scoured areas of substrate, displacement of large coral colonies and impact craters in large coral colonies. Similar to previous cyclone damage assessment methods[9], these characteristics alongside the combined extent and severity of coral colony damage scores (Table 1), have been used to define the damage levels described in this report. Coral damage was defined as Levels 1-5 and structural damage was defined as Levels 3-5 (Figure 3). Further details of the damage categories is presented in the section on *Detailed Observations and Results*.

Table 1: ***Cyclone damage matrix.*** Coral damage extent and severity scores in light blue represent the survey area that was damaged (damage extent) and the predominant type of colony damage observed in the survey area (damage severity description). Damage levels represent ecological impact groupings and encapsulate both colony and reef damage. For example, damage level 3 applies to either minor reef damage (e.g. 11-30% of colonies damaged) or high coral damage (31-50% branches or >75% tips). Coral damage levels 1 and 2 indicate partial colony mortality. Reef damage levels 3, 4 and 5 indicate the increasing extent of complete colony mortality and reef framework damage (Figure 6).

DAMAGE MATRIX	Damage extent						
Damage Severity Description	SCORE	0%	1-10%	11-30%	31-50%	51-75%	76-100%
None	0	0	0	0	0	0	0
Tips / Edges	1	0	10	30	50	75	100
Branches / Parts	2	0	20	60	100	150	200
Colonies	4	0	40	120	200	300	400

Damage Levels	
0	No Damage
1	Minor Coral Damage
2	Moderate Coral Damage
3	High Coral Damage / Minor Reef Damage
4	Severe Coral Damage / Moderate Reef Damage
5	Extreme Coral Damage / High Reef Damage

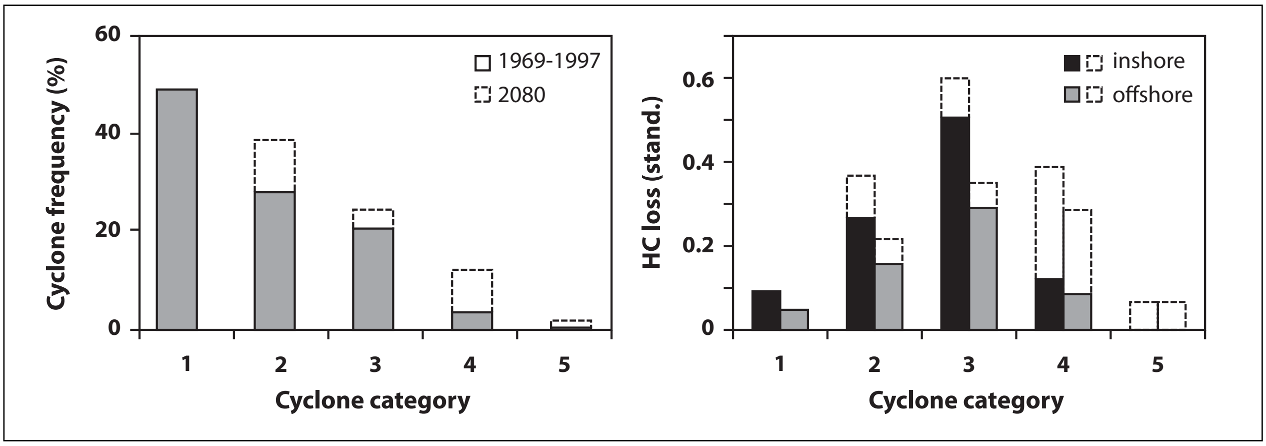


Figure 3: Observed and predicted cyclone intensity distribution and changes in coral cover due to tropical cyclones on the Great Barrier Reef. (a) frequency distribution of tropical cyclones on the Great Barrier Reef (observed 1969 – 1997 grey bars)[6,10,11] and with an increase in half a category of cyclone intensity by 2080 (white dashed bars)[23]. (b) reef-wide loss of coral cover on inshore and offshore reefs based on cyclone intensity distributions from 1969 – 1997 (black and grey bars), and as predicted for 2080 (white dashed bars)[6,10,23]. [figure reproduced courtesy of Fabricius *et al*.[6]]

The survey data were stored in the Integrated Eye on the Reef (iEotR) database, recently developed by GBRMPA and QPWS. A damage impact matrix was developed to integrate the extent and severity scores into damage categories for each survey (Table 1). The matrix and damage categories were developed to be comparable to that developed by AIMS to assess the impact of TC Ingrid[9]. The matrix is also integrated into data visualisation outputs (reef health Google Earth layers) derived from the iEotR database. The survey results were used to estimate the extent and severity of cyclone damage to the total reef area within the Marine Park, which totals 24,839km^2. The proportion of each level of cyclone damage seen within the surveys was extrapolated to the known reef area within the Marine Park (Table 2). Reef damage level results for each reef were grouped by distance from the eye of TC Yasi to produce regional summary pie charts (Figure 2) and a comparison of cross-shelf impact patterns (Figure 4).

Table 2: ***Cyclone damage levels and reef area affected.*** The estimated area and proportion of the Great Barrier Reef Marine Park reef area that sustained coral and reef damage from TC Yasi.

Damage Level	Damage Categories	Total Reef Area Affected (km^2)	Proportion of Affected Reef Area Within the Marine Park (%)
Level 0	No Damage	21,005	84.5
Level 1	Minor Coral Damage	1,388	5.6
Level 2	Moderate Coral Damage	933	3.8
Level 3	High Coral Damage and Minor Reef Damage	564	2.3
Level 4	Severe Coral Damage and Moderate Reef Damage	447	1.8
Level 5	Extreme Coral Damage and High Reef Damage	502	2.0

DETAILED OBSERVATIONS AND RESULTS

SCALE AND SPATIAL PATTERNS OF THE DAMAGE

The surveys documented various levels of coral damage throughout the 89,090 km^2 area of the Marine Park exposed to damaging (gale force to very destructive) winds of TC Yasi. In total, just over 15 per cent (3,834 km^2) of the 24,839km^2 reef area within the Marine Park is estimated to have sustained some level of coral damage, with six per cent (1,513 km^2) of reef area sustaining severe coral damage and some degree of structural damage as a result of TC Yasi (Table 2).

Location of reefs in relation to the eye of a cyclone is an important determinant of the amount of ecological damage caused by its passage[16]. Consistent with previous studies, damage severity and the proportion of sites suffering severe damage caused by TC Yasi tended generally to increase with proximity to the track of the eye of the cyclone, with a tendency for more damage to the left of direction of travel of the cyclone (for the southern hemisphere; in the northern hemisphere greater forces occur to the right)[16].

Reef structural damage was primarily confined to reefs within the areas of destructive and very destructive winds that occurred between Cairns and Townsville (Table 1, Figure 2). The most significant damage occurred at the 61 coral reefs that were in the very destructive and destructive wind zones (Figure 2). Of these reefs, 58 (95 per cent) suffered severe damage to living coral communities, with structural damage evident at 47 (78 per cent) of the 61 reefs exposed to the very damaging winds. Reefs exposed to the very destructive winds south of the cyclone eye (on the left side in relation to the direction of travel) showed the most severe impacts, with 45 – 55 per cent of surveys within 100 km of the cyclone eye recording at least high coral damage and some degree of reef structural damage (Figure 2). To the north, damage was a little less severe with 35 – 45 per cent of surveys within 100 km of the eye recording some degree of structural damage (Figure 2).

The severity of damage was substantially lower at reefs more than 250 km from the cyclone eye, with no structural damage recorded in surveys of reefs south of Townsville (Figure 4). Accordingly, the proportion of surveys recording minor damage or no damage increased with distance south of the eye of the cyclone (Figure 4). To the north of the cyclone's centre the pattern was less obvious. Survey teams found a general decrease in the proportion of sites with structural damage as they moved further north from the cyclone's centre. However, there was not a strong trend in the proportion of surveys recording minor or no coral damage, with only 10 per cent of surveys finding relatively undamaged reefs at sites 150 km from the cyclone centre (Figure 4). This is likely to reflect the high proportion of sites characterised by fragile forms of corals in surveys of reefs offshore of Cairns.

Shelf position also influenced the nature and extent of damage from TC Yasi. There tended to be more severe damage at outer shelf reefs compared to mid shelf reefs, at least among reefs closer to the eye of the cyclone. However, mid shelf reefs sustained structural damage across a wider range of latitude bands than outer shelf reefs. Consistent with this was the observation that surveys recorded minor or no coral damage across a larger range of latitude bands for outer shelf reefs than mid shelf reefs (Figure 4).

Damage from cyclones is typically highly variable in space[16]. The reef damage caused by TC Yasi was severe, extensive and patchy. There tended to be large differences in the amount of damage observed at survey sites within any single reef, with this intra-reef patchiness being greater at reefs farthest from the path of the cyclone eye. As for most physical disturbances, reef sites that were dominated by more fragile corals (such as staghorn and plate *Acropora sp.*) often had much more damage than those characterised by more robust species (encrusting and massive corals), even if these sites were close to each other. In some instances, the survey team encountered sites that suffered only minor colony damage within 100 m of sites at which live coral cover had been reduced to less than five per cent (Figure 5). This heterogeneity in damage tended to be much higher on reefs outside the very destructive wind zone, suggesting that reef orientation and morphology provides greater potential for shelter when wind and resultant wave forces are less strong. Consistent with this was the observation that damage was noticeably more uniform on offshore reefs just south of the

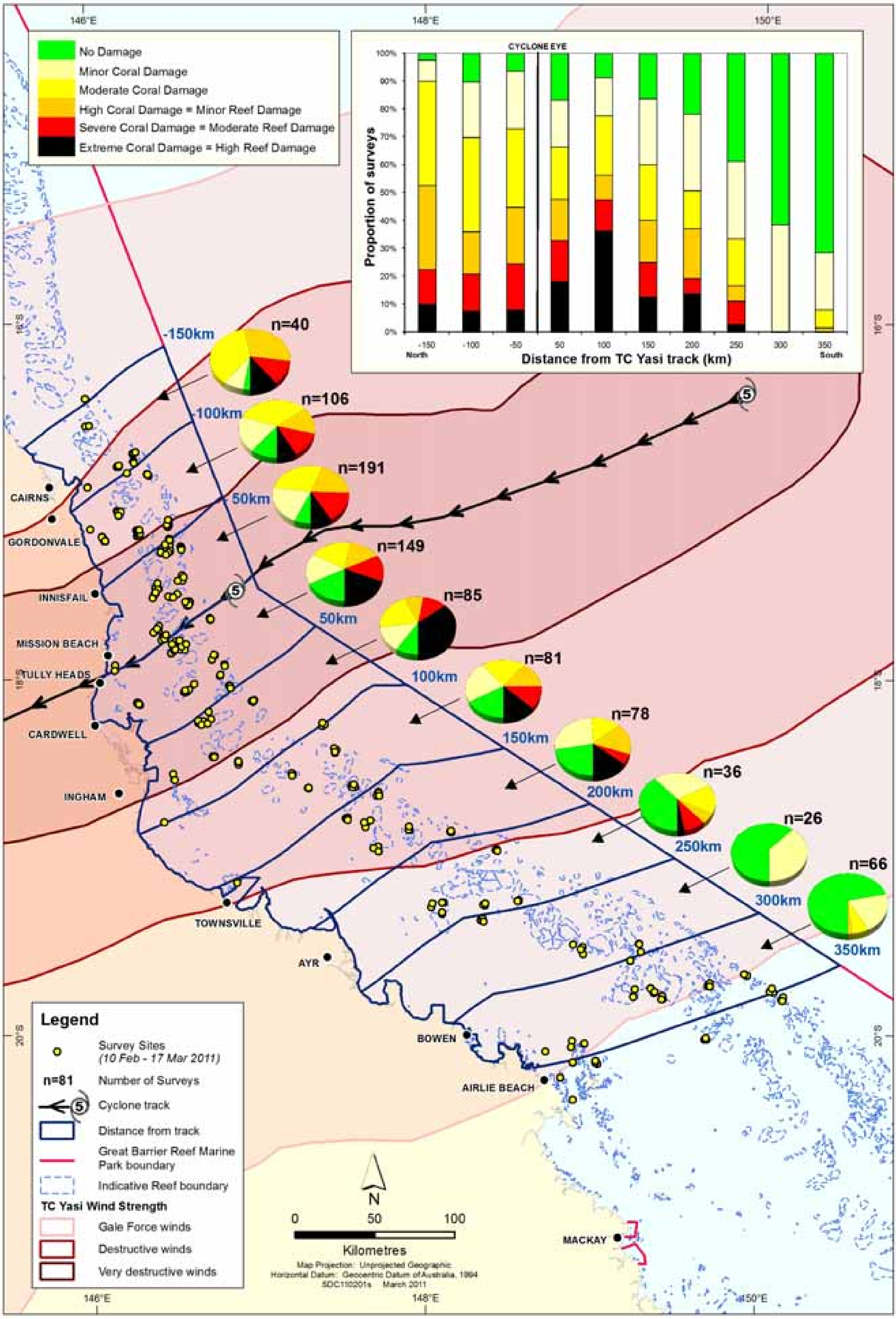


Figure 4: TC Yasi survey sites 10th February – 17th March 2011. Pie charts represent the proportion of surveys that recorded each level of damage for each 50 km Marine Park segment to the north and south of the eye of TC Yasi. The histogram provides a stacked composite of the pie charts to clearly illustrate the damage pattern across the survey area.

Damage Level 0 (No damage): Healthy reef.

Damage Level 1 (Minor damage): Some (1-30%) corals partially damaged; primarily broken tips and some branches or plate edges.

Damage Level 2 (Moderate damage): Many (31-75%) corals partially damaged; most fragile colonies have tips or edges broken, some branches missing or as large rubble fragments.

Damage Level 3 (High damage): Up to 30% of colonies removed, some scarring by debris, soft corals torn, coral rubble fragments from fragile and robust coral lifeforms.

Damage Level 4 (Severe damage): Many (31-50%) colonies dead or removed, extensive scarring by debris, rubble fields littered with small live coral fragments, soft corals severely damaged or removed and some large coral colonies dislodged.

Damage Level 5 (Extreme damage): Most (51-100%) corals broken or removed, soft corals removed and many large coral colonies dislodged.

Figure 5: The six damage levels used in the TC Yasi assessment and analysis. The damage levels were used to evaluate the damage caused by TC Yasi and are comparable to previous studies of cyclone damage on the reef.

centre of the cyclone track, where we recorded near-complete absence of corals and other sessile organisms at the majority of sites surveyed, and very few sites with only minor damage.

CHARACTERISTICS OF THE DAMAGE

Damage from TC Yasi ranged from minor tissue injuries at the edges and tips of fragile coral colonies to total removal of all sessile organisms and abrasion and fracturing of the reef substrate. Across all the wind boundaries, fast growing, more fragile coral life-forms, such as branching and plating *Acropora* corals, sustained the most significant damage, whilst more robust, slow growing corals such as encrusting *Montipora* and massive *Porites* and *Favites* corals were less severely damaged.

At sites with minor coral damage (Damage Level 1), robust corals such as *Porites* and *Favites* and encrusting corals such as many species of *Montipora* were largely undamaged, and even fragile coral colonies such as tall staghorn (*Acropora*) corals, fine needle (*Seriatopora*) corals and large plate (*Acropora*) corals often suffered only minor injuries to branch tips or plate edges (Figure 3). There were generally no signs of damage to the underlying reef structure at these sites. In total, 20 per cent of site surveys recorded this low level of coral damage. This equates to approximately six per cent of the reef area of the Marine Park suffering Level 1 reef impacts. These sites tended to occur furthest from the cyclone, or on sheltered aspects of reefs. Sites with Level 1 damage were occasionally seen at reefs close to the eye of the cyclone, but only in areas that were heavily sheltered by adjacent reef structures (Figure 4).

At sites with moderate coral damage (Damage Level 2), the majority of corals with fragile growth forms had their tips broken or plate segments missing (Figure 3). Some corals had branches broken off and there were large fragments of living or recently dead coral lying loose on the substrate, indicating some colonies had been badly damaged. Robust coral growth forms commonly showed signs of physical abrasion or physical impact, but injuries were largely superficial. There were generally no signs of damage to the underlying reef structure. In total, 21.1 per cent of site surveys recorded this moderate level of coral damage. This equates to approximately 3.8 per cent of the reef area of the Marine Park suffering Level 2 reef impacts. Sites with Level 2 damage were located throughout the survey area, but generally were either in moderately sheltered areas or in areas exposed to less damaging winds (Figure 4).

At sites with high coral damage (Damage Level 3), there were commonly signs that coral colonies had been completely removed by the forces of waves and wave-born debris (Figure 3). Accumulations of broken coral fragments and fresh rubble were often recorded, indicating substantial damage to both fragile and robust corals. Remnants of large soft corals were evidence that large sections of these thick leathery colonies had been torn off the reef. Thick plate-forming corals such as some species of Porites were commonly broken and isolated sections of reef structure were freshly scoured or scarred by impact with wave-born debris. In total, 14.2 per cent of site surveys recorded this high level of coral damage and minor structural damage. This equates to approximately 2.3 per cent of the reef area of the Marine Park suffering Level 3 reef impacts. Sites with Level 3 damage were found throughout the areas exposed to very destructive, destructive and gale force winds (Figure 4).

At sites with severe coral damage (Damage Level 4), few corals escaped substantial physical injury, and many were so severely damaged that only their bases or remnant sections remained attached to the reef (Figure 3). The majority of large soft corals had either suffered substantial tissue loss or had been completely removed, as evident by layers of spicules formed where the coral had been attached to the substrate. Often extensive fields of freshly formed rubble, including large numbers of coral fragments still covered in live tissue, were seen at these sites. Large massive corals and coral bommies that had been recently dislodged were often recorded at these sites, with some showing large cracks or splits. Large patches of reef structure were freshly scoured or scarred by impact with wave-born debris. In total, 11.1 per cent of site surveys recorded severe coral damage and moderate structural damage. This equates to approximately 1.8 per cent of the reef area of the Marine Park had suffered Level 4 damage. Sites with Level 4 damage were found throughout the areas exposed to very destructive, destructive and gale force winds (Figure 4).

At the worst affected sites (Damage Level 5), few corals or other sessile organisms remained attached to the reef structure, aside from the ubiquitous filamentous algae (Figure 3). Large areas of reef structure were comprehensively scoured, with many signs of major abrasion and impact from wave-borne debris. The survey teams also observed large corals, some likely to be hundreds of years old, that had been dislodged and overturned. In total, 11.8 per cent of site surveys recorded these extreme levels of coral damage and high levels of damage to the reef structure. This equates to approximately two per cent of the reef area of the Marine Park suffering this level of damage.

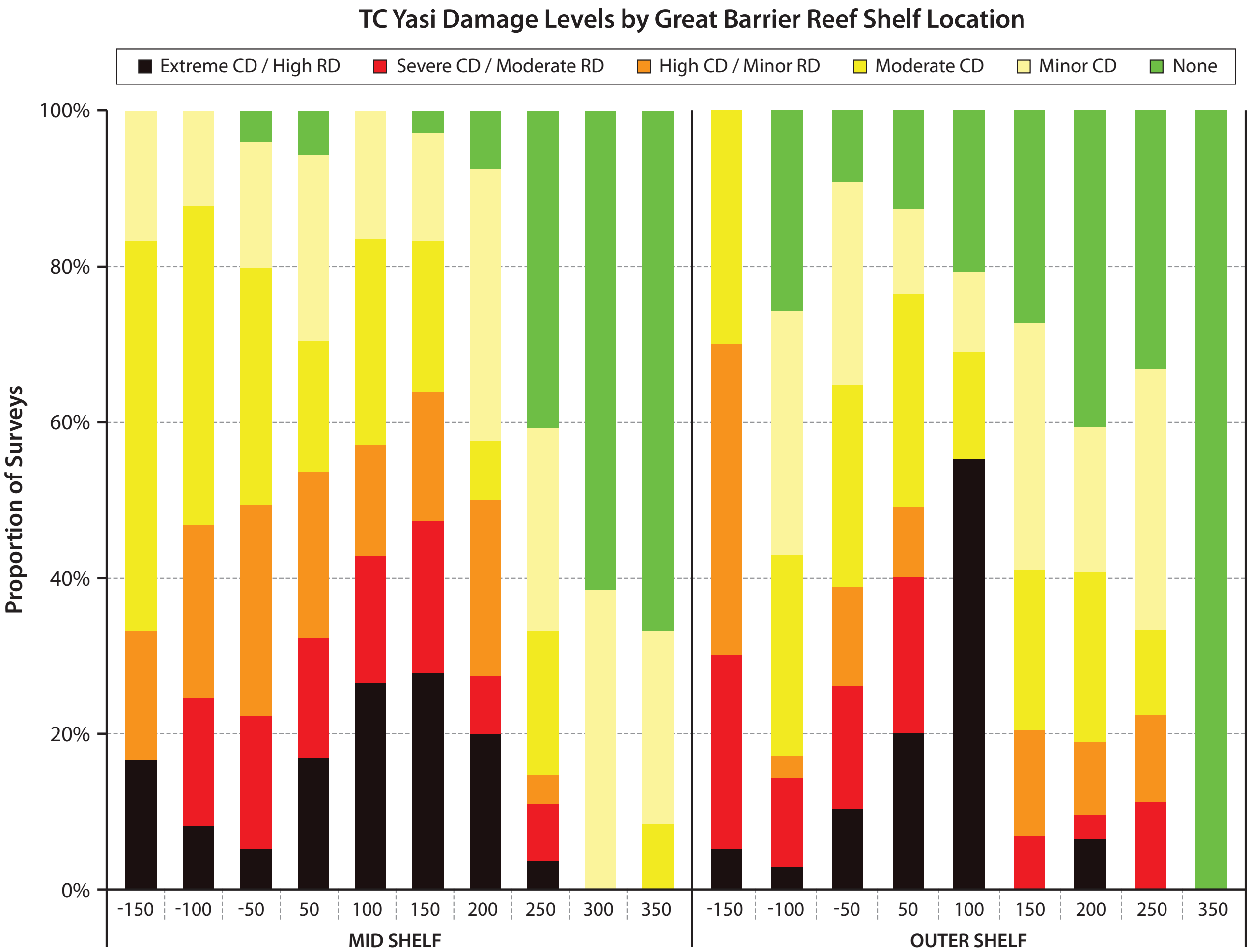


Figure 6: The proportion of reef health impact surveys that recorded each level of cyclone damage, separated by Marine Park shelf location and site distance (in km) from the eye of TC Yasi (negative = north of tc yasi).

These worst affected sites were more likely to occur on exposed aspects of isolated reefs in outer shelf areas exposed to very destructive and destructive winds (Figure 4).

The survey teams also observed extensive growth of algae on many of the damaged reefs (Figure 6). The green filamentous algae was observed growing over remnant coral fragments and injured colonies, and blanketing large areas of damaged reef substrate. Dense growth was seen on reefs up to 300 km south of the cyclone track. The morphology of the algal growth varied with depth, taking the form of a low mat on the mid and lower reef slope, and dense stands of long filaments on the upper slope and reef flat. It is likely that the extensive and ubiquitous nature of this bloom of benthic filamentous algae was facilitated by a dramatic increase in available nutrients. An increase in nutrients could result from upwelling of nutrient rich waters or re-suspension of nutrient-laden sediments by the cyclone, as well as from decomposing organic matter such as the tissues from organisms killed during the storm. The different morphology of the algal growth is likely to be a result of grazing (which is usually less intense in shallow and intertidal areas). The survey teams observed fish apparently feeding on the algae at many sites. Samples of the algae have been submitted to specialists for identification.

CONCLUSIONS AND IMPLICATIONS

Overall, this rapid impact assessment has documented widespread but patchy damage throughout the 15 per cent of the Great Barrier Reef Marine Park affected by TC Yasi. Our surveys found that approximately six per cent of reef area (1,513 km^2) in the Great Barrier Reef suffered significant damage as a result of the cyclone. Fortunately, reefs in key tourism areas such as Port Douglas, Cairns and the Whitsunday Islands were in the 94 per cent of reef area that escaped major impacts from TC Yasi.

CORAL REEF ECOSYSTEMS

The nature and pattern of damage caused by TC Yasi was comparable to that reported from previous cyclones on the Great Barrier Reef[9]. Damage was dramatic and comprehensive at the worst affected sites, which were most common in the very destructive wind zone to the south of the eye of the cyclone. Sites with only minor or no damage could be found throughout the survey area, but were most common beyond the destructive wind zones. However, the majority of sites surveyed were somewhere between these extremes, with moderate to severe levels of coral damage and minor or no structural reef damage.

A major difference between the impacts of TC Yasi and most other cyclones is the sheer scale of damage. Most other studies have reported damage spanning less than 200 km of reef; damage from TC Yasi stretched over 400 km. The only other cyclone known to have caused damage on a similar spatial scale is TC Hamish, which travelled along the southern Great Barrier Reef in 2009.

Despite the ecosystem-scale significance of the damage caused by TC Yasi, we expect the Great Barrier Reef will demonstrate natural resilience at the scale of individual reefs. Recovery of reefs after physical damage generally occurs through a combination of regrowth of damaged colonies and fragments, and recolonisation through larval recruitment. The majority of sites surveyed still had remnants of living coral, which have the potential to accelerate recovery of the coral community. Overgrowth by filamentous algae and establishment of disease can increase the risk that damaged corals will die and reduce the likelihood of surviving fragments and damaged colonies contributing to recovery[14]. In any event, larval recruitment will play a major role in reef recovery at all sites, except those with the least damage. The prospects for larval-driven recovery will be enhanced by the abundance of sites that were recorded as having significant concentrations of largely intact corals, as well as their proximity to severely damaged sites[22]. However, the scale of damage from this cyclone may have implications for the rate of recovery through larval recruitment. At sites free from additional stresses, signs of recovery through larval recruitment can be expected within three to five years. Return to substantial coral cover at severely damaged sites is likely to take 10 years or more, while it can take even longer for recovery to pre-cyclone species diversity[1,8,14,17].

This assessment is one of only a few surveys to document the ecological impacts of a severe cyclone on the Great Barrier Reef[9,23,24,25] – and the only one to record ecological damage from such a large and intense cyclone crossing the Queensland coast as category 5. As a result, much of the insight about the role of storms in coral reef dynamics of the Great Barrier Reef derives from studies of storms and cyclones of relatively low intensity and short return intervals [16,2617]. The current study provides a valuable basis for understanding the scale of impact and the potential for recovery.

CORAL REEF RECOVERY

While coral reefs have evolved under a regime of frequent physical disturbance (and perturbations such as storms and low-intensity cyclones are actually important to the maintenance of biodiversity[8,14]) the ecological implications of disturbances of the scale of TC Yasi are largely unknown. At the level of individual reefs, the processes and timeframes for recovery can be inferred from previous studies. However, the broader ecosystem implications of damage to the extensive system of linked habitats within the affected area are unlikely to be fully understood for a decade or more.

For individual habitats and reefs, the rate of recovery following physical damage is strongly influenced by location, and by associated biological and physio-chemical conditions[14,27,28,29]. For example, previous research has shown that recovery rates on offshore reefs are around 1.5 times faster than inshore reefs due to differences in the larval settlement dynamics and the abundance of competing algae[9,13]. Severe or frequent recurrence of additional disturbances, such as storms, crown-of-thorns starfish outbreaks and coral bleaching events, can significantly hinder community recovery[8,14,15,29,30]. Chronic stresses, such as reduced herbivory and increased sedimentation, as well as increased algae, can also affect recovery by hindering processes essential to coral recolonisation, such as

A) BRAMBLE REEF – VERY DESTRUCTIVE WIND ZONE

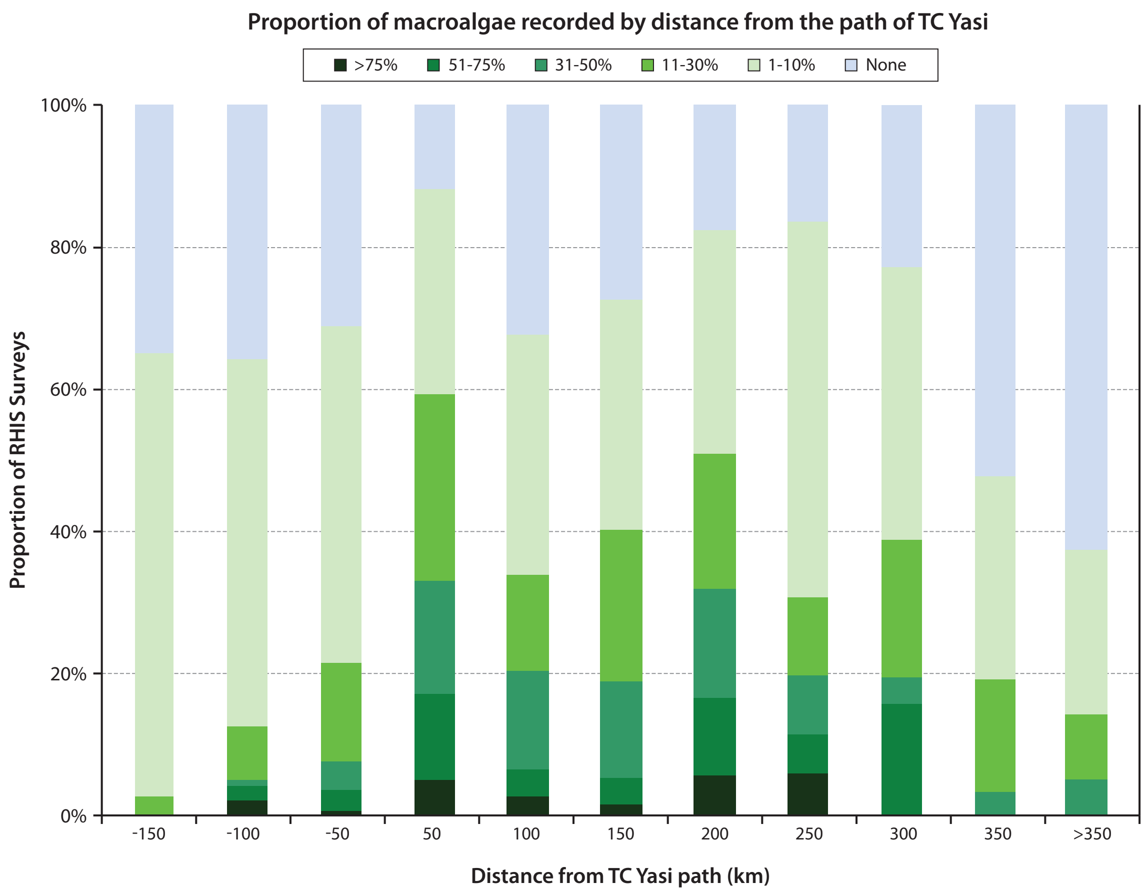
B) DIP REEF – DESTRUCTIVE WIND ZONE

Figure 7: Photographs taken 50 m apart show examples of the patchiness and intensity of TC Yasi's damage in both a) the very destructive wind zone and b) the destructive wind zone.

settlement and survival of coral recruits, and growth and survival of adults[14,28,31]. Many of the reefs affected by TC Yasi, particularly those on the outer part of the shelf, are relatively free from chronic stresses. However, progress in halting and reversing the degradation of water quality around damaged reefs will be especially important to improving the prospects of recovery of inshore reefs that have been damaged by TC Yasi.

It is likely that TC Yasi has caused more damage to the Great Barrier Reef than any single event since at least the early 1900s. However, TC Yasi was not the only cyclone to affect the Great Barrier Reef Marine Park early in 2011; TC Anthony (category 2) crossed the coast 300 km to the south of TC Yasi only four days earlier. The combined footprint of gale force winds for TC Yasi and TC Anthony stretch for more than 750 km from Cooktown to Mackay. Additionally, the destructive core of TC Yasi passed over several remote reefs and cays in the Coral Sea including those in the Coringa-Herald National Nature Reserve and Willis Island. It is likely these reefs were also substantially affected by strong waves and currents generated by the passage of the cyclone.

As a result of the large scale of impacts of TC Yasi and TC Hamish, it is likely that storm damage has now surpassed crown-of-thorns starfish as the largest cause of coral mortality on the Reef over the past two decades (Figure 7). The scale of impacts caused by these extreme intensity storms takes on extra significance in light of concerns that climate change could increase the frequency of severe cyclones over the course of this century[7]. Modelling suggests that an increase in cyclone intensity by half a category would result in 50 – 60 per cent greater cyclone-related loss in coral cover both inshore and offshore (compared to present rates and assuming full recovery between events) (Figure 8)[16]. Over coming decades severe cyclones can be expected to cause further severe damage more often to more reefs in the Great Barrier Reef.



IMPLICATIONS FOR MANAGEMENT AND INDUSTRIES

While storms are a normal part of the Great Barrier Reef environment, cyclones of the intensity and size of TC Yasi have historically been rare events, recurring every 200-300 years or more[2]. The impacts of climate change on cyclone formation and behaviour remain an area of active research, but there is growing concern that warming oceans will result in an increase in the frequency of extreme-intensity cyclones[5,6,19]. Yet, cyclones are not the only risk predicted to increase in frequency due to climate change. Coral bleaching events, already attributed with causing severe and lasting damage to 18 per cent of the world's coral reefs [32,33], are projected to increase in frequency and severity over the course of this century[33], compounding the effects of cyclones, ocean acidification and other disturbances such as crown-of-thorns starfish outbreaks.

The cumulative effect of these influences is that coral reefs around the world, including the Great Barrier Reef, will spend increasing amounts of time in various phases of ecological recovery. Although many of these impacts are driven by forces beyond the control of reef managers, modelling studies clearly show that local management will play an increasingly crucial role in the fate of coral reefs affected by large-scale disturbances[1] such as cyclones, crown-of-thorns starfish outbreaks, coral bleaching[34] and ocean acidification[35]. In the face of these large-scale external challenges, the resilience of coral reef systems like the Great Barrier Reef is crucial to their future.

In recognition of the increasing pressures associated with global change, the GBRMPA has built a management regime focused on building the resilience of the Reef. Prime amongst a suite of major initiatives is the joint Australian and Queensland governments' *Reef Water Quality Protection Plan*. This strategic, collaborative program aims to address the issue most important to reef resilience, especially those in inshore areas: water quality[14,15]. There are many global examples of damaged reefs in poor water quality areas that fail to recover and instead shift from coral to algae dominated communities[9,14]. These phase shifts can have dramatic consequences for the sustained provision of ecosystem goods and services, as well as being very difficult – if not impossible – to reverse[10]. The *Reef Water Quality Protection Plan* aims to halt and reverse the degradation of water quality in the Great Barrier Reef Lagoon, and thereby situate the Reef to be more resilient to stresses outside management control, such as cyclones and coral bleaching events.

Another key influence on the resilience of reefs around the world is overfishing, especially of herbivores such as parrotfishes, surgeonfishes and rabbitfishes[10]. Excess removal of key functional groups like herbivores increases the risk that the ecosystem will undergo a 'phase shift' from coral-dominated to algae-dominated reef[9,14]. This is especially important following major coral mortality events, when algae can quickly take over a reef in the absence of adequate herbivory. Fortunately, fishing pressure on herbivores remains negligible in the Great Barrier Reef, and commercial fishing of other species, such as coral trout, is subject to tight controls including quotas and management plans[15]. Together with the rezoning of the Reef in 2004 (which increased the coverage of no take zones from five per cent to 33 per cent), Reef-wide efforts to ensure sustainable fishing practices and improve water quality are major initiatives that are supporting the resilience of the Reef to cyclones and other climate-related events.

A range of local actions are also underway to support Reef resilience and to build stewardship. These include a resilience assessment and mapping project in the Keppel Islands which has involved community members in developing resilience assessment tools and actions that support the resilience of local reefs. Stewardship programs such as Eye on the Reef and Reef Guardians are also important to increase the capacity of local communities to understand and support the health of their local reefs. The partnership between GBRMPA and the QPWS is particularly important as it provides a multi-jurisdictional platform for involving Reef users and community members in the protection of the Great Barrier Reef ecosystem for future generations.

Reef users, such as tourism operators and fishers, are key partners in building the resilience of the Great Barrier Reef. Accordingly, a key component of the Extreme Weather Response Program has been to collect information on the implications for Reef users of ecological impacts caused by extreme weather events. A project to understand the social and economic implications of TC Yasi is currently being implemented as part of the Extreme Weather Response Program. This project has been developed in response to reports of substantial impacts on commercial fishing operators and tourism businesses that are dependent on islands and reefs affected by TC Yasi. Anecdotal reports indicate the effects of the cyclone include a dramatic decrease in catch rates for commercial fishers targeting live coral trout, an observation consistent with impacts on fisheries reported for TC

Hamish[20]. Tourism operators in areas directly in the path of the cyclone have also reported severe damage to beaches and fringing reefs that were integral to their tour offerings. Both of these industries are also suffering from broader commercial challenges such as a decrease in visitation to the region and reduced market prices for key fish species, reducing their ability to cope with the impacts of TC Yasi. It is hoped involving these sectors in efforts to understand the impacts of TC Yasi will increase knowledge of risks and opportunities in relation to events such as cyclones and assist them to adapt to future climate-related impacts.

These studies, in combination, aim to increase our understanding of the implications of major climate-related events for the Great Barrier Reef and the industries and communities that depend on it. By integrating this knowledge into management thinking and activities, the Extreme Weather Response Program, implemented in partnership with QPWS, industry and researchers, aims to support efforts to build the resilience of the Reef, enhance stewardship and increase the adaptive capacity of Reef users. It is through these collaborative and integrative approaches that GBRMPA and its partners hope to improve the outlook for the Great Barrier Reef as we move through this century of change.

APPENDIX 1:
Reef Health and Impact Survey Reporting Form

Reef Health and Impact Point Survey

Australian Government
Great Barrier Reef Marine Park Authority

Queensland Government

25 cm 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0

OBSERVER AND SITE DETAILS

Observer name/s:		Date:
Organisation:	Vessel:	Sheet: .... of: ....
Email:	Phone:	Snorkel ☐ or Dive ☐

Site information *Centre of survey* *Check one*

Lat: .... S — Decimal Degrees (preferred) ☐
Long: .... E — Degrees Decimal Mins ☐ / Degrees Min Sec ☐

Reef ID: — Marine Park Zone:
Reef name:
Site:

SITE CONDITIONS:

Survey depth: .... m
Visibility: *(Circle one)* < 5m / 5-10m / >10m
Secchi: .... m
Air temp: .... °C
Water temp (0-3m): .... °C
(5-10m): .... °C
Flood plume: Y / N
Suspended algal bloom: Y / N
Tide at survey time (low/mid/high): ....

HABITAT:

Lagoon:	A
Crest:	B
Slope:	C
Bommie field:	D
Reef flat:	E
*Other:	F

** Please describe:*

BENTHOS:

Macroalgae:	.... %
Live coral:	.... %
Recently dead coral:	.... %
Live coral rock:	.... %
Coral rubble:	.... %
Sand:	.... %
TOTAL:	100 %

BENTHOS

Macroalgae observations — Present: Y / N — Photos taken: Y / N

MACROALGAE TYPE:	Slime	Entangled / mat-like	Filamentous	Leafy / fleshy	Tree / bush-like	Total
Proportion of the total macroalgae cover	%	%	%	%	%	100 %
Average height (cm)*						

* Macroalgae height: A = 0-3cm B = >3-25cm C = >25cm

Coral observations — Present: Y / N — Photos taken: Y / N

CORAL TYPE:	Soft coral	Branching	Bushy	Plate / table	Vase / foliose	Encrusting	Massive	Mushroom	Total
Proportion of the live coral cover	%	%	%	%	%	%	%	%	100 %

IMPACTS

Coral bleaching — Present: Y / N — Photos taken: Y / N

CORAL TYPE:	Soft coral	Branching	Bushy	Plate / table	Vase / foliose	Encrusting	Massive	Mushroom
Proportion of the live corals that are bleached	%	%	%	%	%	%	%	%
Severity of the bleaching *								

* Bleaching severity: 1 = bleached only on upper surface 2 = pale/fluoro (very light or yellowish) 3 = totally bleached white 4 = recently dead coral lightly covered in algae

Coral disease — Present: Y / N — Photos taken: Y / N

Proportion of coral cover affected	CORAL TYPE:	Soft coral	Branching	Bushy	Plate / table	Vase / foliose	Encrusting	Massive	Mushroom
%	Black band disease								
%	Brown band disease								
%	White syndromes								
%	Other disease / tumours								

(Number of affected colonies)

Coral predation — Present: Y / N — Photos taken: Y / N

				CORAL TYPE: Soft coral	Branching	Bushy	Plate / table	Vase / foliose	Encrusting	Massive	Mushroom
Proportion of coral cover affected	PREDATOR:	Total # adult	Total # juvenile	Number of affected colonies							
%	COTS										
%	*Drupella*										

Recent coral damage — Present: Y / N — Photos taken: Y / N

Proportion of coral cover affected	CORAL TYPE:	Soft coral	Branching	Bushy	Plate / table	Vase / foliose	Encrusting	Massive	Mushroom
%	Number of affected colonies								
	Severity of damage* *Insert code*								
	Possible cause** *Insert code*								

* Severity: 1 = Edge / tips 2 = Part / branches 3 = Whole colonies

** Possible cause: A = Anchor D = Divers S = Snorkellers W = Weather / storm V = Vessel C = Animal X = Other U = Unknown

Rubbish — Present: Y / N — Photos taken: Y / N

RUBBISH TYPE:	Fishing line	Plastic	Netting	Rope	Other
Number of pieces of rubbish:					

Additional information *(For example: site conditions, impacts, sightings of protected species and comments on supplied photographs)*

11/2010

Please return to: **Great Barrier Reef Marine Park Authority** | PO Box 1379 Townsville QLD 4810 | Fax: (07) 4772 6093 | Ph: (07) 4750 0700 | reefhealth@gbrmpa.gov.au

REFERENCES

1. Osborne, K., Dolman, A.M., Burgess, S.C. and Johns, K.A. 2011, Disturbance and the dynamics of coral cover on the Great Barrier Reef (1995–2009), *PLoS ONE* 6(3): e17516.

2. Nott, J. and Hayne, M. 2001, High frequency of ‘super-cyclones’ along the Great Barrier Reef over the past 5,000 years, *Nature* 413(6855): 508-512.

3. Bureau of Meteorology 2011, *Historical impacts of cyclones on the East Coast,* The Bureau, Melbourne, viewed 17/07/2011, <http://reg.bom.gov.au/cyclone/history/eastern.shtml>.

4. Bureau of Meteorology 2011, *Severe Tropical Cyclone Yasi,* The Bureau, Melbourne, viewed 17/07/2011, <http://reg.bom.gov.au/cyclone/history/yasi.shtml>.

5. Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K. and Sugi, M. 2010, Tropical cyclones and climate change, *Nature Geoscience 3*: 157-163.

6. Webster, P.J., Holland, G.J., Curry, J.A., Chang, H.R. 2005, Changes in tropical cyclone number and intensity in a warming environment, *Science* 309: 1844-1846.

7. Knutson, T.R. and Tuleya, R.E. 2004, Impact of CO^2-induced warming on simulated hurricane intensity and precipitation: sensitivity to the choice of climate model and convective parameterization, *Journal of Climate* 17(18): 3477-3495.

8. Connell, J.H., Hughes, T.P. and Wallace, C.C. 1997, A 30-year study of coral abundance, recruitment, and disturbance at several scales in space and time, *Ecological Monographs* 67(4): 461-488.

9. Fabricius, K.E., De'ath, G., Puotinen, M.L., Done, T.J., Cooper, T.F. and Burgess, S.C. 2008, Disturbance gradients on inshore and offshore coral reefs caused by a severe tropical cyclone, *Limnology and Oceanography* 53(2): 690-704.

10. Hughes, T.P., Rodrigues, M.J., Bellwood, D.R., Ceccarelli, D., Hoegh-Guldberg, O., McCook, L.J., Moltschaniwskyj, N., Pratchett, M.S., Steneck, R.S. and Willis, B. 2007, Phase shifts, herbivory, and the resilience of coral reefs to climate change, *Current Biology* 17(4): 360-365.

11. Hughes, T.P., Graham, N.A.J., Jackson, J.B.C., Mumby, P.J. and Steneck, R. 2010, Rising to the challenge of sustaining coral reef resilience, *Trends in Ecology and Evolution* 25(11): 633-642.

12. Hughes, T.P., Baird, A.H., Bellwood, D.R., Card, M., Connolly, S.R., Folke, C., Grosberg, R., Hoegh-Guldberg, O., Jackson, J.B.C., Kleypas, J.A., Lough, J.M., Marshall, P.A., Nystrom, M., Palumbi, S.R., Pandolfi, J.M., Rosen, B. and Roughgarden, J. 2003, Climate change, human impacts, and the resilience of coral reefs, *Science* 301: 929-933.

13. Diaz-Pulido, G., McCook, L.J., Dove, S., Berkelmans, R., Roff, G., Kline, D.I., Weeks, S., Evans, R.D., Williamson, D.H. and Hoegh-Guldberg, O. 2009, Doom and boom on a resilient reef: Climate change, algal overgrowth and coral recovery, *PLoS ONE* 4(4): e5239.

14. Hughes, T.P. and Connell, J.H. 1999, Multiple stressors on coral reefs: a long-term perspective, *Limnology and Oceanography* 44(3): 932-940.

15. Great Barrier Reef Marine Park Authority 2009, *Great Barrier Reef outlook report 2009,* Great Barrier Reef Marine Park Authority, Townsville.

16. Puotinen, M. 2007, Modelling the risk of cyclone wave damage to coral reefs using GIS: a case study of the Great Barrier Reef, 1969-2003, *International Journal of Geographical Information Science* 21(1): 97-120.

17. Done, T. 1992, Effects of tropical cyclone waves on ecological and geomorphological structures on the Great Barrier Reef, *Continental Shelf Research* 12(7-8): 859-872.

18. Sweatman, H.P.A., Cheal, A.J., Coleman, G.J., Emslie, M.J., Johns, K., Jonker, M., Miller, I.R. and Osborne, K. 2008, *Long-term monitoring of the Great Barrier Reef: status report,* Australian Institute of Marine Science, Townsville.

19. Emanuel, K. 2005, Increasing destructiveness of tropical cyclones over the past 30 years, *Nature* 436: 686-688.

20. Tobin, A., Schlaff, R., Tobin, R., Penny, A., Ayling, T., Ayling, A., Krause, B., Welch, D., Sutton, S., Sawynok, B., Marshall, N.A., Marshall, P.A. and Maynard, J.A., 2010, *Adapting to change: minimising uncertainty about the effects of rapidly-changing environmental conditions on the Queensland Coral Reef Fin Fish Fishery,* Fishing and Fisheries Research Centre, James Cook University, Townsville.

21. Bureau of Meteorology 2011, *Tropical cyclones: frequently asked questions,* The Bureau, Melbourne, viewed 17/07/2011, <http://www.bom.gov.au/cyclone/faq/index.shtml>.

22. Connolly, S.R. and Baird, A.H. 2010, Estimating dispersal potential of marine larvae: dynamic models applied to scleractinian corals, *Ecology* 91(2): 3572-3583.

23. Great Barrier Reef Marine Park Authority 2010, *Observed impacts from climate extremes on the Great Barrier Reef—Summer 2008/2009,* Great Barrier Reef Marine Park Authority, Townsville.

24. Van Woesik, R., De Vantier, L.M. and Glazebrook, J.S. 1995, Effects of Cyclone 'Joy' on nearshore coral communities of the Great Barrier Reef, *Marine Ecology Progress Series* 128: 261-270.

25. Done, T.J., Ayling. A.M. and Van Woesik, R. 1991, *Broadscale survey of impacts of Cyclone Ivor on coral reefs,* Great Barrier Reef Marine Park Authority, Townsville.

26. Puotinen, M.L., Done, T.J. and Skelly, W.C. 1997, *An atlas of tropical cyclones in the Great Barrier Reef region, 1969-1997,* CRC Reef Research Centre, Townsville.

27. DeVantier, L.M., De'ath, G., Turak, E., Done, T.J. and Fabricius, K.E. 2006, Species richness and community structure of reef-building corals on the nearshore Great Barrier Reef, *Coral Reefs* 25: 329-340.

28. Hauri, C., Fabricius, K.E., Schaffelke, B. and Humphrey, C. 2010, Chemical and physical environmental conditions underneath mat- and canopy-forming macroalgae and their effects on understorey corals, *PloS ONE* 5(9): e12685.

29. Done, T. 1993, On tropical cyclones, corals and coral reefs, *Coral Reefs* 12(3): 126-126.

30. Rogers, C.S. and Miller, J. 2006, Permanent 'phase shifts' or reversible declines in coral cover? Lack of recovery of two coral reefs in St. John, US Virgin Islands, *Marine Ecology Progress Series* 306: 103-114.

31. Connell, J.H. 1997, Disturbance and recovery of coral assemblages, *Coral Reefs* 16(Suppl.): S101-S113.

32. Carpenter, K.E., Abrar, M., Aeby, G., Aronson, R.B., Banks, S., Bruckner, A., Chiriboga, A., Cortes, J., Delbeek, J.C., DeVantier, L., Edgar, G.J., Edwards, A.J., Fenner, D., Guzman, H.M., Hoeksema, B.W., Hodgson, G., Johan, O., Licuanan, W.Y., Livingstone, S.R., Lovell, E.R., Moore, J.A., Obura, D.O., Ochavillo, D., Polidoro, B.A., Precht, W.F., Quibilan, M.C., Reboton, C., Richards, Z.T., Rogers, A.D., Sanciangco, J., Sheppard, A., Sheppard, C., Smith, J., Stuart, S., Turak, E., Veron, J.E.N., Wallace, C., Weil, E. and Wood, E. 2008, One-third of reef-building corals face elevated extinction risk from climate change and local impacts, *Science* 321(5888): 560-563.

33. Hoegh-Guldberg, O. 2010, Coral reef ecosystems and anthropogenic climate change, *Regional Environmental Change* 11: 215-227.

34. Wooldridge, S. 2009, Water quality and coral bleaching thresholds: Formalising the linkage for the inshore reefs on the Great Barrier Reef, Australia, *Marine Pollution Bulletin* 58: 745-751.

35. Anthony, K.R.N., Maynard, J.A., Diaz-Pulido, G., Mumby, P.J., Marshall, P.A., Cao, L. and Hoegh- Guldberg, O. 2010, Ocean acidification and warming will lower coral reef resilience, *Global Change Biology* (5): 1798-1808.